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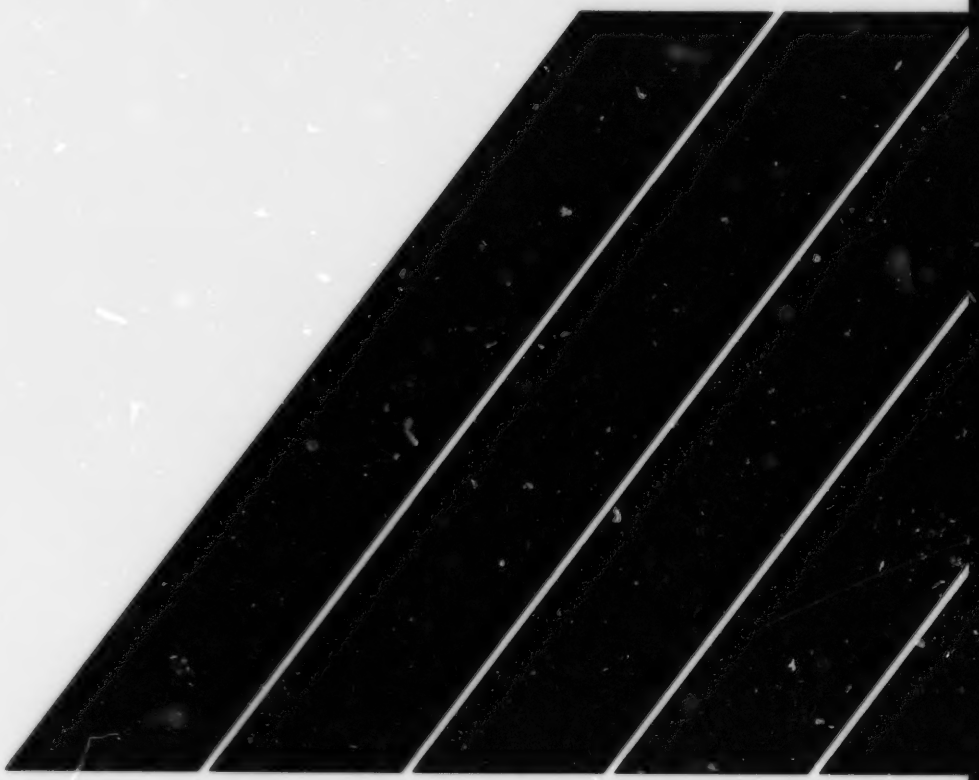
NONINTRUSIVE TEST FOR WINDOW GAS-FILL LEVEL: FEASIBILITY STUDY



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NONINTRUSIVE TEST FOR WINDOW GAS-FILL LEVEL: FEASIBILITY STUDY

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PREFACE

This report considers the technical feasibility of measuring the gas-fill level of a multiglazed window unit without physically rupturing the sealed unit. The report establishes which technology is capable of solving this problem and outlines what further experiments should be performed before a commercial instrument is built.

The energy savings which can be realized by converting to gas-filled insulated-glass windows is substantial on a national scale. However, there is a need for portable, inexpensive test equipment which can be used in the plant for quality control, in long-term field-performance tests, in quality assurance at the construction site, in standards laboratory testing of new fabrication materials/procedures, etc.

At present, a window unit is usually punctured, and a sample of the gas extracted for analysis in order to determine the gas fill level. This procedure is undesirable since the resealing patch is a weak point. There is only one quantitative gas-level measurement which is nonintrusive - the Raman test used by Cardinal IG. This Raman measurement is suitable for standards testing, but because of its cost and the need for vibration isolation it is not suitable for field tests or production line quality control.

We have measured the thermal, acoustic, and electrical properties of a sample window using approaches that, in some instances, are novel to this problem. We have found that a measurement of the time-of-flight of a single high frequency sound signal and the electric discharge potential are relatively inexpensive solutions to the gas-level measurement problem. In addition, they are equally adaptable to field work, quality control or standards testing. Consequently, they offer a general solution for both industry and government regulators.

ABSTRACT

The objective was to find a nonintrusive technique for determining the gas content of an insulated glass unit. The thermal conductance measurements for argon-air gas mixtures with over 80 percent argon yield no information on the argon content. On the other hand, thermal conductance measurements might be useful with SF6 or other heavier gases. Acoustic measurements which are novel to this field indicated that the resonance properties of the window cavity are not a useful approach. However, acoustic time-of-flight measurements across the window cavity yield gas-content levels with a precision of a few percent for heavy gases. Unfortunately, both the thermal and these acoustic approaches have poor sensitivity with argon, the most common gas. For argon gas content, an electric discharge technique yields a precision of a few percent and with some further tests can reach a precision of 0.1 %. In addition, we recommend a coupled optical measurement of the light emitted by the electric discharge. This measurement is applicable to all gases that might be used in the future such as krypton. In summary, we outline inexpensive nonintrusive techniques that can be used for quality control and standards testing of energy efficient window units.

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EXECUTIVE SUMMARY

In general the gas content of a window unit is determined by puncturing the gas seal and removing a sample for analysis. The repair of this puncture is not as secure or reliable as the overall construction. Consequently, a better product can be obtained if a nonintrusive test can be developed both for quality control and for long-term field-performance tests.

A Raman measurement does exist for quantitative nonintrusive testing, but this equipment is expensive, requires a high level of technical expertise and is only suitable for laboratory applications. This report investigates alternative techniques that are less expensive to implement and are capable of being used in field surveys to check quality assurance of the product and to assess the long-term integrity of the unit.

We considered several physical properties of the filling gas - thermal, acoustic and electrical. A measurement of the thermal conductance will indicate whether the unit is above 75 % filled with argon and provides a quantitative measure of its fill level below 75 % with acceptable accuracy. However, this method is slow and does not give a precise measure above 75 % argon content. Manufacturers achieve a 95 - 100 % argon fill so that a typical leakage of less that 0.5 % argon loss per year guarantees at least a 20 year life span for the unit before the argon level drops below 75 % and thermal performance begins to deteriorate significantly. Hence the thermal conductivity does not have any sensitivity in the region of most interest. In addition, variability of the energy efficient coatings on the glass will also affect the thermal conductance and this effect might not be easily separated. Consequently, unconventional techniques were studied.

Two acoustic techniques were considered. Firstly, the window cavity was considered as a resonance cavity with a standing wave pattern. However, there were too many vibration modes, other than the fundamental cavity mode, present for this method to yield reliable estimates. A second sound technique, the time-of-flight of a sound pulse through the window, was easier to interpret, since the direct transit signal was isolated. For a heavy gas such as SF6 a precision of 2 % on the gas content can be achieved, but for light gases such as argon the precision is only 20 %.

The electrical breakdown voltage was measured as a function of air-argon gas mixtures for plate electrodes on the outer glass surfaces of the window unit. The value of the breakdown voltage changes rapidly with the argon content. The argon content can be measured to a precision of 0.1 %. This precision is comparable to the Raman technique, but is achieved at a fraction of the equipment cost. Since the electric discharge technique does not work well with insulators such as SF6, the electric discharge technique and the acoustic time-of-flight technique form a

complimentary pair.

Before the full precision of the electric discharge technique can be realized a number of further tests are required to investigate the possible long-term effects of the discharge on the low emissivity coating or any other tints, coatings, films, screens, etc. that might be utilized. Furthermore, there is a time-dependent conditioning phenomena whose origin has not been identified. To circumvent these potential problems small internal electrodes placed in the corner spacer should be considered. Finally, we recommend that a spectral analysis of the light which is associated with the electrical discharge might improve the precision and yield detailed information on the individual components of the gas.

In summary, this report outlines and evaluates alternative strategies for measuring the gas content of energy efficient windows. Solutions are proposed which are less expensive, faster, and more easily implemented than either the existing nonintrusive Raman measurement or the standard puncture test.

RESUME POUR LA DIRECTION

En général, le contenu en gaz d'une fenêtre est déterminé par rupture du joint d'étanchéité et prélèvement d'un échantillon pour analyse. La réparation de cette rupture n'est pas aussi sûre et fiable que l'ensemble de la construction. Par conséquent, il est possible d'obtenir un meilleur produit en menant au point un essai non intrusif de contrôle de la qualité et de vérification à long terme du rendement sur le terrain.

Il existe une mesure Raman de contrôle non intrusif quantitatif, mais l'équipement est cher, exige une grande compétence technique et ne convient qu'aux applications en laboratoire. Ce rapport examine d'autres techniques d'application moins coûteuse, utilisables pour vérifier la qualité du produit et évaluer son intégrité à long terme.

Nous avons étudié plusieurs propriétés physiques (thermiques, acoustiques et électriques) du gaz de remplissage. Une mesure de la conductance électrique indique si le produit est rempli à plus de 75 % d'argon et permet de mesurer quantitativement le niveau de remplissage en deçà de 75 % une précision acceptable. Cependant, la méthode est lente et ne mesure pas avec précision les contenus d'argon supérieurs à 75 %. Les fabricants atteignent des niveaux de remplissage de 95 à 100 % de sorte qu'avec une fuite type d'argon de moins de 0,5 % par an, ils offrent sur le produit une garantie d'au moins 20 ans avant que le niveau d'argon chute en deçà de 75 % et que le rendement thermique diminue sensiblement. Ainsi, la conductivité thermique est peu sensible dans la région d'intérêt. En outre, la variabilité des revêtements à rendement énergétique élevé sur les vitrages influe sur la conductance thermique, effet difficile à isoler. Par conséquent, des techniques nouvelles ont été étudiées.

Deux techniques acoustiques ont été examinées. Premièrement, le volume de gaz dans la fenêtre a été considéré comme une cavité résonante caractérisée par une régime d'ondes stationnaires. Or, les modes de vibration, autres que le mode fondamental de la cavité, dans cette méthode, étaient trop nombreux pour produire des estimations fiables. Une deuxième technique acoustique, exploitant le temps de parcours d'une onde sonore dans la fenêtre, a été plus facile à interpréter, le signal transitoire direct étant isolé. Pour un gaz lourd comme le SF6, on a établi le contenu en gaz à 2 % près, mais pour des gaz légers comme l'argon, la précision n'est que de 20 %.

La tension électrique de rupture a été mesurée en fonction de mélanges gazeux air-argon pour des électrodes planes sur la face extérieure des vitrages de la fenêtre. La valeur de la tension de rupture varie rapidement en fonction du contenu en argon. Le contenu en argon peut être mesuré à 0,1 % près. Cette précision est comparable à celle de la technique de Raman, mais elle est atteinte à une fraction du coût du matériel. Comme la technique de la décharge électrique convient mal aux isolants comme le SF6, elle complète bien la technique du temps de parcours acoustique.

Avant d'atteindre la pleine précision de la technique de la décharge électrique, il faut mener d'autres essais pour examiner les effets à long terme possibles de la décharge sur le revêtement de faible émissivité ou tout autre revêtement, pellicule, teinte, écran, etc. qui pourrait être utilisé. Il y a en outre un phénomène de conditionnement lié au temps dont l'origine reste inconnue. Pour contourner ces problèmes éventuels, il faudrait envisager la pose de petites électrodes internes dans les cale de coin. Enfin, nous recommandons l'analyse spectrale de la lumière associée à la décharge électrique pour améliorer la précision et recueillir plus d'information sur chaque constituant du gaz.

En résumé, ce rapport décrit et évalue des stratégies de remplacement pour mesurer le contenu en gaz des fenêtres à rendement énergétique élevé. On y propose des solutions moins coûteuses, plus rapides et plus faciles à appliquer que les méthodes existantes de la mesure Raman non intrusive et de l'essai de rupture standard.

INTRODUCTION

To improve performance, some window manufactures in North America fill their insulated glass (IG) units with special gases. Typically sulphur hexafluoride (SF6) is used where sound insulation is important while argon is used for thermal insulation. The benefits of thermal insulation are gaining universal acceptance by window manufacturers and consumers alike, since thermal performance enhancements of 15 to 25 percent can be achieved with an argon fill[1]. On a national scale, this improvement is significant and can be increased further by the use of heavier gases.

This report addresses the problem of monitoring the gas content of an IG unit. Gas content measurements are desirable for several reasons -- quality control at production, quality assurance at the construction site before and after installation, long term field tests, accelerated weathering studies, etc. Most measurements of the gas content require that the window seal be punctured to obtain a gas sample. A method is needed to determine the gas content in the cavity without destroying the integrity of the seal. Consequently, we have investigated several measurement techniques that are nonintrusive. The nonintrusive test also has the advantage of being adaptable to in situ field tests.

At present, manufacturers of IG units take considerable care to ensure that their units are hermetically sealed. There are different construction and gas fill techniques used by the industry. A typical assembly process involves the following stages (A detailed discussion of performance affecting parameters in the assembly of IG units can be found in Ref. 2-4). If the glazing has a low emissivity (low-e) coating, the cut glass is etched along its edge. This both prevents the silver in the low-e coating from oxidizing and provides a clean surface for sealant adhesion. One of the spacer bars has two holes drilled and temporarily plugged while one or more of the other spacer bars are filled with a desiccant. The spacer bars are assembled with corner inserts and a bead of polyisobutylene is applied to each of the sides that will receive a glass pane. After adding the glass the unit is pressed and a second sealant such as polysulfide is applied over the outer edge, coating both glass edges and the spacer bar. The window unit is left undisturbed while the sealants cure. Then the filling plugs in the spacer bar are removed, the gas is injected, and these plugs are resealed. The window is left for 24 hours before testing its gas content. In the final production stage, a needle is inserted into one of the filling-hole plugs in order to extract a gas sample for an O_2 paramagnetic resonance measurement (servomex oxygen meter). This puncture then has to be sealed. Since the hole created by the needle is small, it is difficult to ensure a good seal. It was the elimination of the potential degradation of the unit by this

final step that initially prompted our search for a nonintrusive test.

During the course of our study, we became aware of two techniques which are now in use for nonintrusive measurements. The first, named KONAR, is a prototype being developed by Herbert Eicher of Ratioteknik, Braunschweig, West Germany under contract with McKeegan Equipment and Supply Inc. of Plymouth, MI[2]. This is ongoing research and as yet KONAR is not available commercially. This device is based on the spark, or electrical discharge, created inside of the IG unit when a tesla coil's probe is placed against the glass pane. The authors[2] state that KONAR requires a low-e coating on one pane and that it works only for pure argon filling. An additional limitation is that KONAR does not provide a reading of the argon content; it only indicates whether the IG unit meets or exceeds a preset standard.

A second nonintrusive measurement has been implemented by Cardinal IG of Minneapolis, MN[3]. They focus monochromatic light onto the gas in the IG unit and look at the scattered light signal. Using the Raman scattering phenomenon, the wavelength for resonant scattering off either the O_2 or N_2 molecules is a well defined signature of the presence of either gas. With this technique, they achieve a precision of around 0.2 % after five scans. Their absolute detection limit of approximately 0.1 % is about 10 times better than the servomex tester which senses the less abundant O_2 molecule. However, this added precision is gained at the cost of requiring some vibration isolation and an optical table with costly state of the art technology. Like the servomex tester the Raman instrument does not measure the argon content directly. The argon content is calculated from the measured air content.

There is one other nonintrusive measurement which is referred to as the Linde measurement[2]. In the Linde test, the IG unit is sealed in a chamber which is then filled with a carrier gas such as helium. After 3 to 4 hours the gas is purged and passed through a gas chromatograph to determine the argon content and hence the leak rate of the IG unit. Although this is a measurement of the gas leak rate, rather than the gas content which we are addressing here, it will enter into the later discussion. In accelerated weathering tests the Linde leak rate, a measurement of the gas content and a dew point test for the moisture content are all required measurements.

We have considered three physical properties as the basis for our investigations. Therefore, the method and results portions of this report are grouped into the three categories of acoustic, thermal and electrical techniques.

OBJECTIVES

Our general aim was to determine the feasibility of measuring the gas content of an IG unit with a nonintrusive technique. As an additional constraint, we were searching for simple technology that would lead to instrument costs that would be within any small manufacturer's budget, but would still meet or exceed the precision of existing equipment. Finally, we wanted an instrument that was sufficiently portable to use in the field.

PART A: ACOUSTIC

ACOUSTIC INTRODUCTION

The standard acoustic test, which is used in the window industry, is a measurement of the noise insulation provided by the complete window unit. In that test, the attenuation of the sound's intensity is measured over a wide band of frequencies. In this report we use a specific input frequency from a piezoelectric sound transducer. Furthermore, our approaches use the velocity of sound to characterize the type of gas fill.

The velocity of sound in a gas depends on the pressure of the gas, the density of the gas and the type of gas, whether monoatomic, diatomic or polyatomic. The relationship is given by

$$c = \sqrt{\gamma \cdot P / \rho} \qquad (1)$$

where c = speed of sound
γ = ratio of specific heats = C_P / C_V
P = pressure
ρ = density

For a confined gas such as in the gap between the glazing, the volume is constant and the pressure varies with temperature. In that case the relation is more conveniently written as

$$c = \sqrt{R T (1 + R / C_V) / M} \qquad (2)$$

where R = gas constant
T = absolute temperature
M = molecular weight
C_V = specific heat at constant volume

Table 1 gives the values of the necessary parameters for gases which are used or under consideration for use in IG units. Note that the speed of sound of Argon is 93 % of that of Air and as a result the speed of sound in the gas would have to be measured very accurately to obtain the mixture ratio.

Table 1. Parameters at standard temperature and pressure [6].

	density	gamma	C_p	sound velocity
air	1.2929 kg/m^3	1.403	1002.8 J/kg$^\circ$C	331.5 m/s
argon	1.7837	1.667	524.0	307.6
krypton	3.733	1.667	249.8	212.7
xenon	5.887	1.667	158.1	169.3
SF6	6.602	1.333	667.0	143.0

The objective is to measure the speed of sound for mixtures of the filling gas and air. For a mixture of gases, equation 1 is still used, but with a density representing the weighted mean and with a gamma calculated from the weighted mean values of the specific heats. As an example, for two gases (a) and (b), the velocity is calculated with the following values for γ and ρ:

$$\rho = (N_a \rho_a + N_b \rho_b) / (N_a + N_b) \qquad (3)$$

$$\gamma = \frac{(N_a C_{pa} + N_b C_{pb})}{(N_a C_{va} + N_b C_{vb})} \qquad (4)$$

where N is the number of moles of the gas.

Figure 1 illustrates the dependence on admixtures of air for several relevant gases. About 80 % of gas filled IG units use argon gas whose thermal conductance changes rapidly below a 75 % fill level. As is evident from this figure, in the critical region above 75 % argon content, the sound velocity will not provide a sensitive probe. However, this technique might be useful with heavier gases.

SF6 has a much lower speed of sound than either argon or air and when mixed with them will depress the speed of sound dramatically. The curve in Figure 1 which represents a fill-gas mixture of 40 % SF6 and 60 % argon has a strong variation in velocity even near a full charge of gas. In these calculations, it was assumed that any leak will have air displacing Argon and SF6 in the original proportions. However, depending on where the

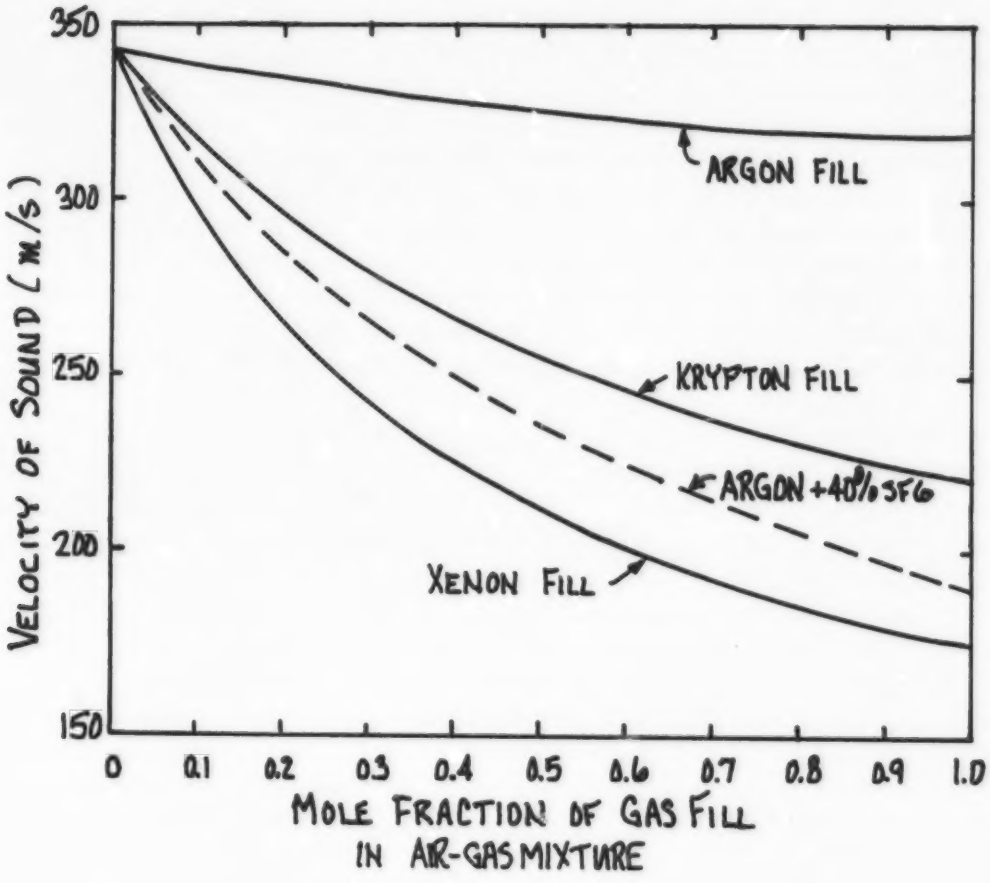

Figure 1. Sound velocity as a function of gas fill for the mixture of 40 % SF6 with 60 % argon and for the three inert gases argon, krypton and xenon.

leak occurs this may not be a valid assumption in a test situation because SF6 is much denser than the other two and could settle to the bottom of the window cavity. A measurement of the diffusion rates for these gases would be useful.

A second factor, which is of primary importance in the use of sound as a probe, is the problem of impedance matching of the sending and receiving transducers to the glass pane. The ratio of the amplitude of the sound transmitted to that incident on a 3 mm thick glass sheet is 0.00013. This must be squared to obtain the sound transmission coefficient for two panes of glass. This can be reduced somewhat by putting the source directly in contact with the glazing using an acoustic coupling fluid or gel.

ACOUSTIC METHOD

Two different methods were used, but in each case the spacing between the two glass panes, d, was required. An average separation was obtained for each of the IG units by taking edge measurements on all sides. An instrument which measured the total thickness at the location of the acoustic readings would have reduced the uncertainty on the gap spacing.

The first method of determining the speed of sound in the gas cavity was based on the wave equation $c = f \lambda$. Because of the high acoustic reflectivity at each glass surface, standing wave patterns can be established. Consequently, by measuring the frequency (f) of the resonant half-wave mode of vibration ($\lambda = 2d$), one can calculate the speed of sound in the gas cavity. The

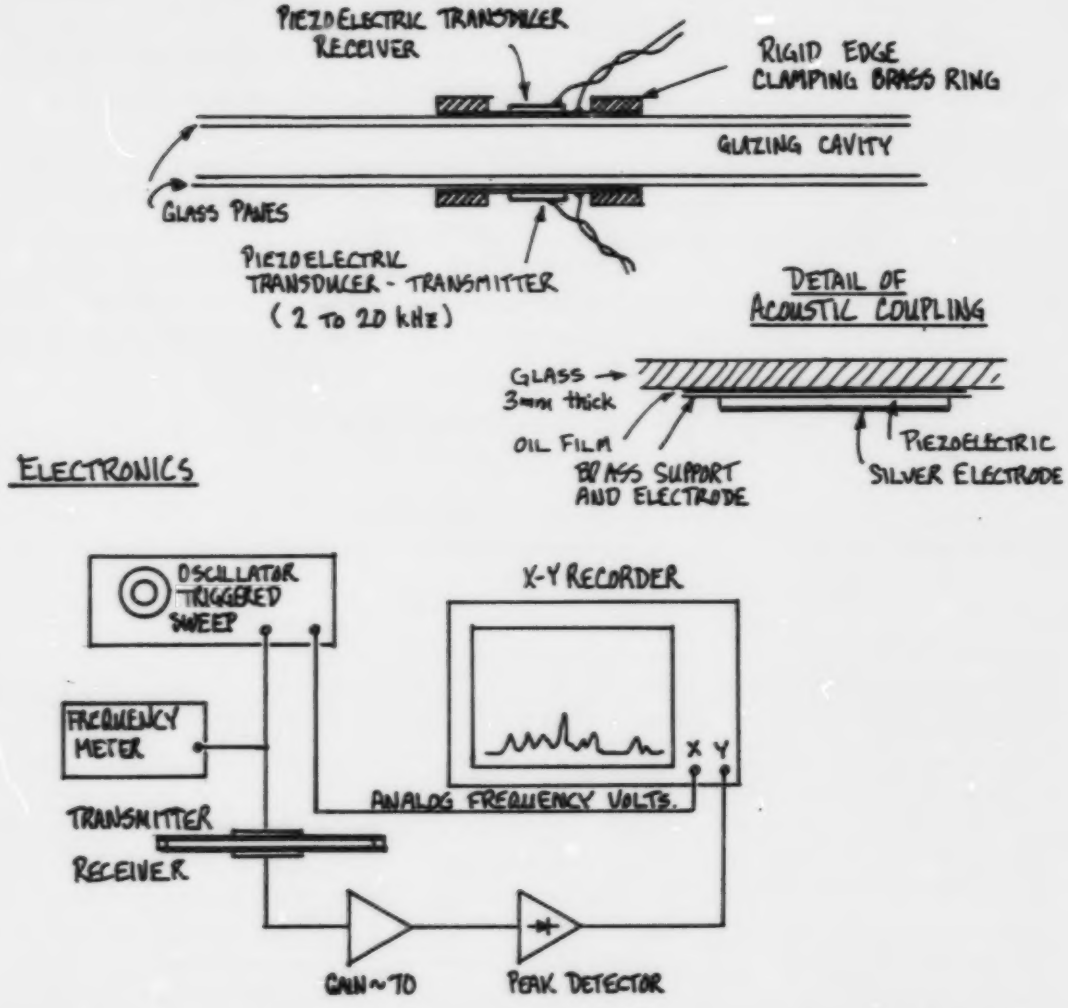

Figure 2. Acoustic resonance transmission source and detector geometry with a schematic of the electronics.

IG unit that we tested had a cavity spacing of d = 15 mm with 3 mm thick glass glazing. This particular IG unit had been supplied by Repla Ltd. of Oakville Ontario a year prior to our tests with a nominal gas mixture of 40 % SF6 and 60 % argon. In the resonance experiments shown in Figure 2 identical modified Archer 273-073 transducers served as source and detector.

The second technique that we investigated was a time-of-flight approach. The idea is to use a sharp pulse and time the delay between transmission and reception of the pulse. In this experiment we used an IG unit obtained from PPG's Halifax plant. It had a spacing of 17.5 mm which corresponds to a flight time of about 51.0 μs in air and 54.9 μs in argon. This difference of 3.9 μs can be easily measured and will be larger for heavier gases.

We used two barium titanate piezoelectric transducers whose fundamental resonant frequency was 668 kHz in order to generate a 100 kHz single sine wave input pulse. We had originally used a higher frequency but could not find the transmitted signal. The

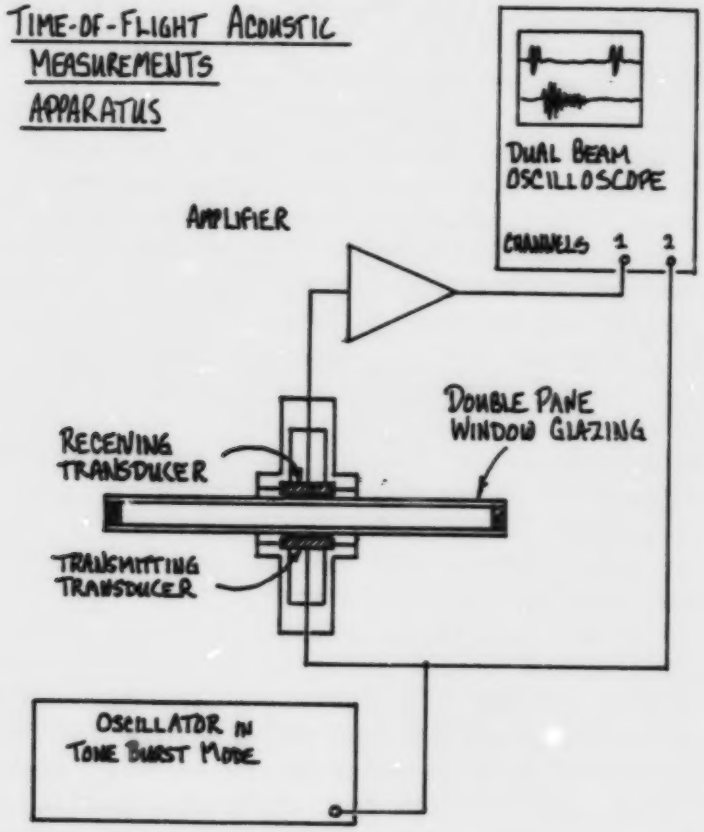

Figure 3. Schematic for sound velocity determination by time of flight technique. The gas replacement apparatus is not shown.

experimental arrangement shown in Figure 3 included a 40 dB amplification of the transmitted signal with low and high frequency cut off filters.

The transducers were coupled to the glass using plasticine, since they were recessed in their housings. We initially used oil but this was abandoned because of electrical contact problems.

Recently, we learned that Don Taylor of Repla Ltd. has found propylene glycol and glycerine useful as acoustic coupling agents. He pointed out that both eliminate water soluble problems for clean-up and have a better viscosity behavior than mineral or petroleum oils.

ACOUSTIC RESULTS

The resonance cavity measurements initially yielded a rich frequency spectrum. The spectrum was not just the simple half-wave standing-wave resonance, but included all other modes of oscillation of the rectangular window cavity plus the vibrational modes of the glass. This made for a very complex spectrum that would have been very difficult to interpret. Hence we took measures to eliminate the unwanted modes.

In Figure 4, we show the change in the transmitted acoustic signal as surface modes of the glass are progressively eliminated. In Figure 4(a) the surface modes on the transmitter side have been damped by using a heavy metal plumbing flange which was attached to the glass using plasticine. In Figure 4(b) a similar steel flange was attached on the detector's side. In Figure 4(c) the detector was decoupled further by ensuring that it did not touch the glass. As one would expect, the received signal is reduced by a factor of 10^{-7} from the value of the transmitted signal.

One clear feature persists at 6 kHz. For d = 15 mm this corresponds to an acoustic resonance wave speed of 180 m/s. Referring to Figure 1, it appears that our sample has a full charge, at the end of one year, with slightly more than the nominal 40 % of SF6. There were no independent confirming tests.

Furthermore, due to the peak width, this resonance frequency can only be estimated to within about 0.1 kHz. This translates into a precision on the sound velocity of approximately 2 % for this argon-SF6 mixture and 1 % for pure argon. Finally, using Figure 1, this converts to a 5 % uncertainty in the level of argon-SF6 mixture but a 20 % uncertainty in the pure argon fill level. This large uncertainty for the argon gas is again due to the sound speed's relative insensitivity to air admixtures above the 80 % argon-fill level. In all gases the sensitivity increases as the gas level decreases. The overall precision could be improved by further amplification of the input signal. On the other hand, any uncertainty in the measured gap spacing will add to the uncertainty in the gas-level estimate.

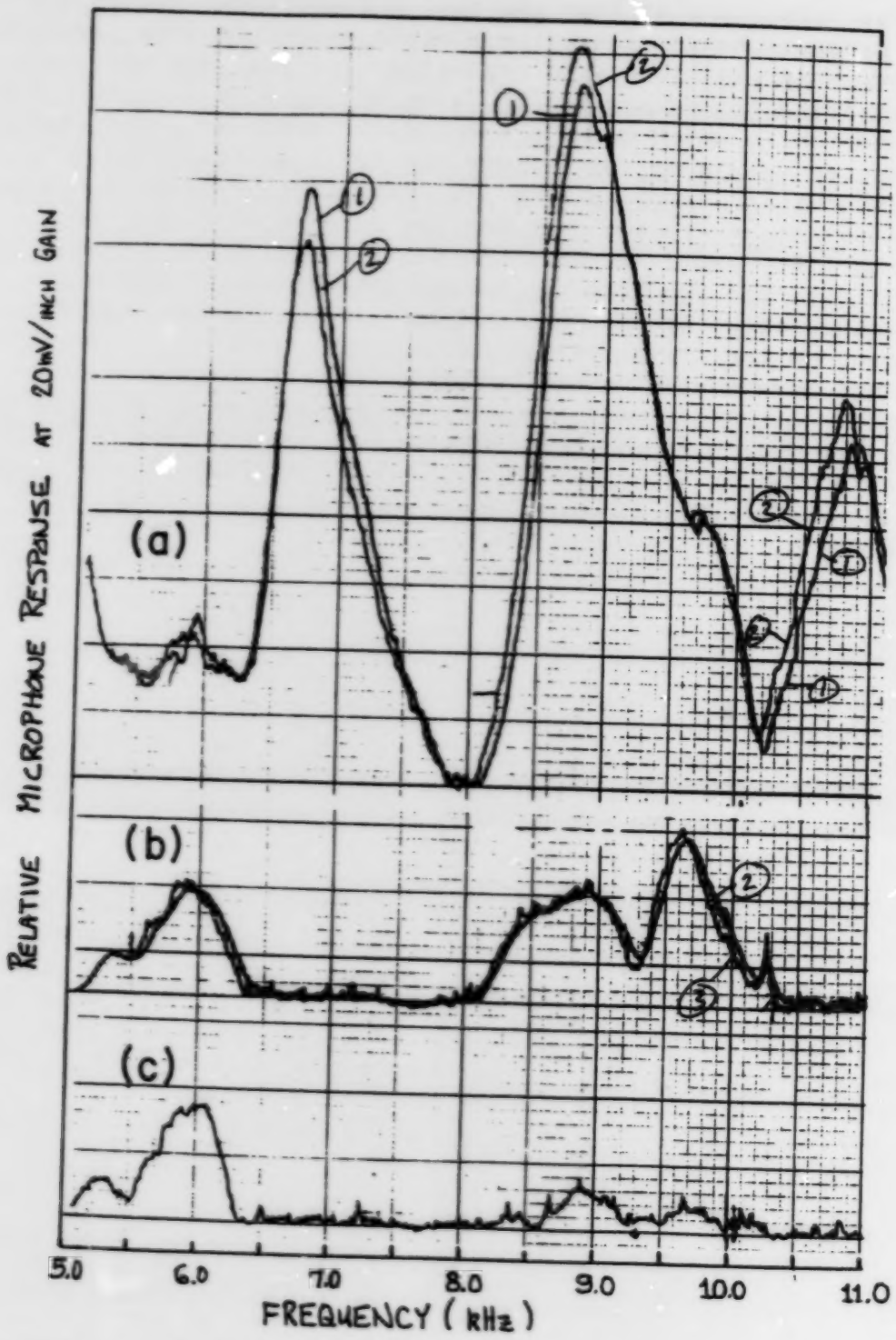

Figure 4. Received signal as a function of transmitting frequency for a 25 cm x 25 cm window with a 15 mm cavity. The effect of increased damping of the glazing is apparent in the sequence (a) to (c).

Because of the relative strength of the acoustic signal from surface modes to that from the gas transmission mode, one must take precautions to remove the surface modes in the measurement rather than in the data reduction. The position of the transmitting transducer and the size of the unit will be critical in determining which modes are excited. Moreover, the receiving transducer should not be in hard contact with the glass.

The curves labelled one to three in Figure 4 refer to different scans without changing the experimental set up. This repeatability would not be achieved if the transducers were moved a centimeter or two from the center between measurements.

Potentially, there are fewer experimental difficulties inherent in the time-of-flight approach. Initially two plastic glazings were tested since plastic had a higher transmission coefficient. Since multiple reflections were clearly visible, the delay time between input pulses was adjusted until successive reflected pulses overlapped and reinforced each other[7]. This created a resonance in the time spectrum that was very well defined. This transmitted pulse had the expected delay of about 50 μs and corrections for transmission through the transducer and plastic were confirmed to be on the order of a micro second.

When we attempted time-of-flight measurements on a glass IG unit, this resonance technique had to be abandoned. In the previous test the plastic glazings had not been rigidly fixed to the plastic spacer ring. With the glass IG unit, interfering signals that travelled along the glass surface and through the aluminum spacers were more intense than the transmitted signal of interest. We had to revert to an input signal that was one cycle of a 100 kHz sine wave.

In the oscilloscope traces displayed in Figure 5(a) and 5(b), the upper curve is the 10 V input signal. The received signal below this has been amplified by a factor of 5×10^3. The small structure on the left is the direct signal, which has been transmitted across the gas-filled gap, while the following signal of larger amplitude is attributed to sound propagation along the glass. This interpretation was confirmed in two ways. With a larger window, 0.61 m x 0.91 m, only the signal along the glass was delayed. Secondly, only the small leading signal shifted when the gas was changed, so the large structure cannot be associated with other resonant modes within the cavity.

In Figure 5(c) the direct transit signal has been further amplified and the time scale expanded. As read from this figure, the arrival time is about 60 μs delayed from the input. Hence there is an additional 10 μs delay introduced by our electronics, the transducers, the plasticine coupling and the glass panes. This delay is not necessarily a problem as systematic offsets can be incorporated into any analysis.

The first minimum in Figure 5(c) is shown in Figure 5(d) on an expanded scale to illustrate the shift in transmitted wave pattern

when air is replaced by argon. This 4 μs shift is in good agreement with the predicted value of 3.9 μs. In achieving this agreement, we have ensured that all other potential variables remained fixed. The size of other possible uncertainties is discussed below.

Two 3 mm glass panes introduce 1.08 μs delay. Hence a variation in glass thickness of 1 % introduces a timing error of 10 ns or 0.25 % on the gas transit time. This is proportionately large for thicker panes.

If one uses a digital storage scope, in place of the analog oscilloscope used here, the signal resolution can be greatly

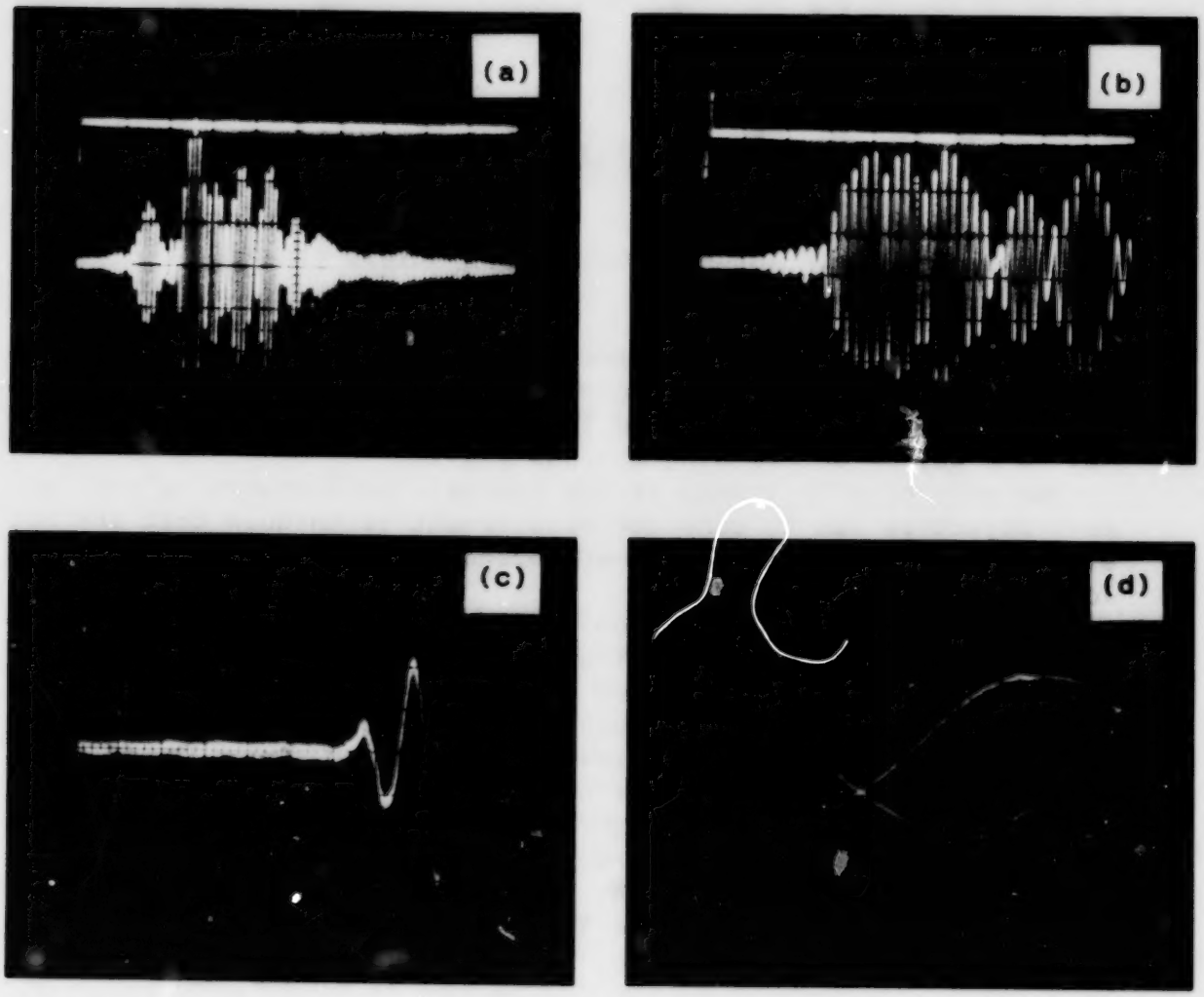

Figure 5. Time-of-flight oscilloscope traces for a 25 cm × 25 cm window with a 17.5 mm space between panes. The sweep speed (horizontal time axis) is (a) 100 μs, (b) 50 μs, (c) 10 μs, and (d) 1 μs per scale division.

enhanced by adding spectra. Furthermore, with good electronics a timing resolution in the nanosecond range can be achieved. Hence, theoretically, there is little limitation on the precision of the time-of-flight measurement from the electronic components. However, with refinements in the electronics the cost of an instrument package increases to the range $ 15,000 - 30,000.

The transducer will be a constant but the coupling of it to the glass could be a critical factor in developing a reliable instrument. Finally, as before, the precision with which the gap spacing is known directly limits any speed of sound estimate.

With regard to figure 5(d), a study of the variation of the amplitude of the transmitted signal for various gas fills, using this time-of-flight approach might be useful.

PART B : THERMAL CONDUCTANCE

THERMAL CONDUCTANCE METHOD

Since the importance of determining the gas fractions in the cavity stems from a need to maintain the thermal resistance of the window, the measurement of the thermal conductance of the window may be a way of determining the gas fill.

We only briefly looked at the thermal conductance since our main objective was to consider measurement techniques that are not already in use and which did not depend upon the properties of the low-e coating.

Sophisticated equipment for this type of measurement exists at the Solar Thermal Engineering Centre at the University of Waterloo. Our equipment, shown in Figure 6, was quite simple.

The double glazing was flushed with a known air-argon mixture for over 10 minutes, as described in detail in Part C of this report. In order to lower the heat flow to as near to zero as possible, the system was brought close to equilibrium by using a heat source at room temperature. The heat flow measurements were initiated when a heat source at about 50 ^{o}C was substituted for the room temperature one. The low emissivity coating was on the upper pane in all measurements.

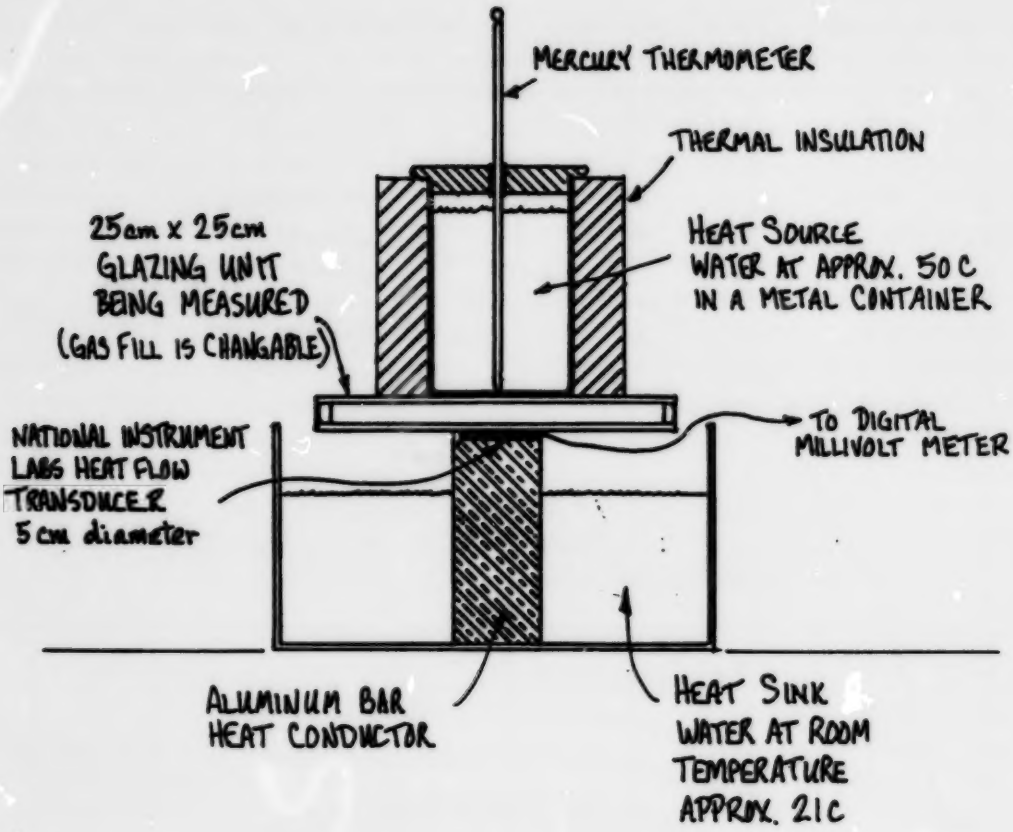

Figure 6. Thermal conductance measuring apparatus.

THERMAL CONDUCTANCE RESULTS

As illustrated in Figure 7, the heat flow increases rapidly as the upper window glazing was warmed under the source. This rate of increase of heat flow was nearly identical for all mixtures of air and argon in the cavity since the rate depended almost entirely on the warming rate of the upper pane. Slowly, after about 30-40 minutes, one approaches an equilibrium heat-flow rate which is determined by the temperature difference between the heat source and the heat sink and by the thermal resistance of the window. All measurements fell on the curves shown in Fig. 7. Finally the data given in Figure 7 includes a radiation component which might not be the same for all gases.

Measurements at four different mixtures of air-argon indicated that the method is not sensitive to gas mixtures near 100 % argon. The conductivity of the IG unit was obtained using the heat flow measurement at 40 minutes in

$$k\ (W/m^2\ ^oC) = 12.6 \times \text{transducer output in mV} / (T_{source} - T_{sink}),$$

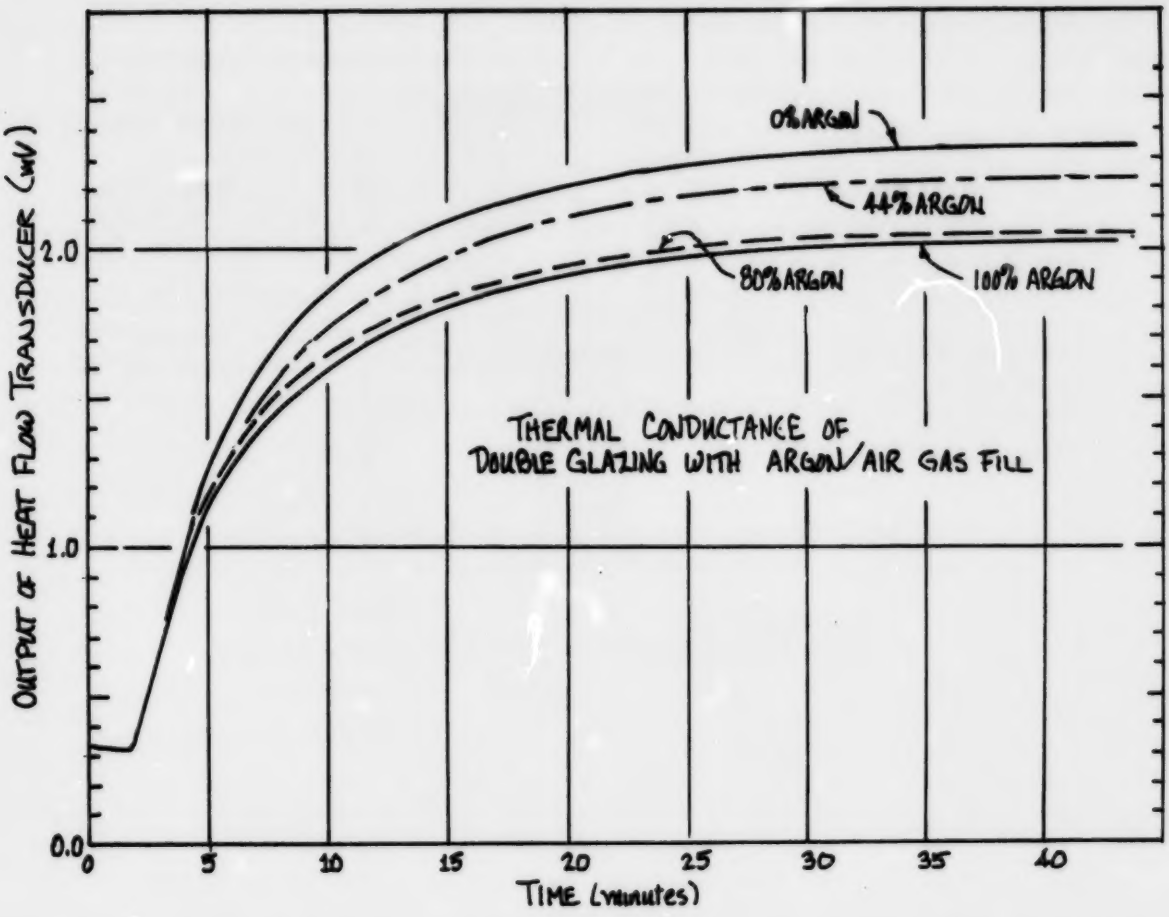

Figure 7. Time variation of heat flow through a double glazed window with a gap of 17.5 mm as a function of gas fill.

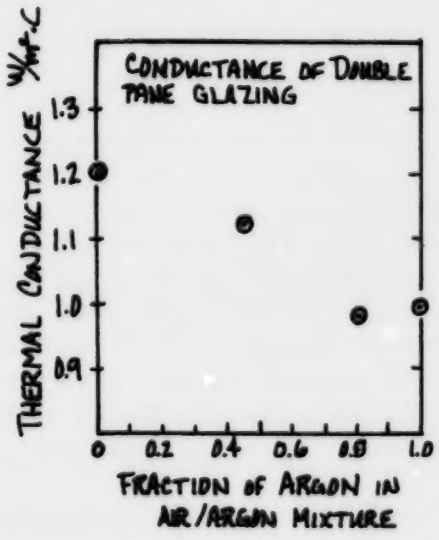

Figure 8. Thermal conductance or U value as a function of gas fill for a 17.5 mm gap.

which includes the calibration of the National Instrument Labs heat-flow transducer. This removes small differences in the source and sink temperatures from run to run.

In Figure 8 the conductivity at 100 % argon is 1 % larger that the value at 80 % argon. These values are equal to within the experimental uncertainties (represented by the circles in this figure). Hence there is little or no variation in conductivity above 80 % argon.

Both the acoustic and thermal responses are determined by the same physical properties, the basic collision dynamics between gas molecules. Consequently, these results for argon are consistent with our acoustic measurements. Again, for heavier gases we would expect a greater sensitivity near 100 % gas fill.

PART C : ELECTRICAL DISCHARGE

ELECTRICAL DISCHARGE METHOD

Air-Argon Gas Mixtures

The compressed gases were supplied by Linde a division of Union Carbide. We used Medical air, CGA type 1 grade F, and argon as primary gases. The flow system had a Fisher and Porter series 10A3135 purge meter on each gas line which was calibrated using a water displacement measurement. Repeated calibration runs indicated that the gas flow could be set to approximately one percent accuracy with this equipment.

Selected flow rates for each gas merged at a T junction. Then the mixing gases continued through 1.4 meters of 6.35 mm tubing to the experimental chamber.

High Voltage Source

Since air requires 30 kV per centimeter to initiate electrical breakdown, high voltages are essential for window gaps that are typically 1 to 2 cm. The voltage has to be large enough to pull electrons off surface atoms (there are not many gas atoms) and accelerate them sufficiently so that upon colliding with a gas atom they knock more electrons free. These cascading events form an electrical discharge or plasma.

In all electrical breakdown tests, a 60 cycle AC high voltage was produced by a step up transformer working off an ordinary mains outlet. As illustrated in Figure 9, a variac was used to manually increase the primary coil voltage on a Jefferson Electric Co. luminous tube transformer. As a safety precaution, the variac control was isolated by the addition of an 8 cm nylon shaft

extension. With this equipment we were limited to voltages below 26.7 kV peak-to-peak. As illustrated later, in Fig. 11, this limited us to mixtures above 85 % argon. A peak-to-peak value of 40 kV or more would have allowed measurements down to 75 % argon content in a standard window.

The voltage to the primary coil was monitored using a Fluke 75 digital meter. The voltage of the secondary coil was also monitored by using a Tektronix P-6015 1000X high voltage probe which was attached to a second Fluke 75 meter. In all measurements, the Fluke 75 meter's rms voltage was scaled by the factor 1.4142 to obtain the peak voltages which appear in this report.

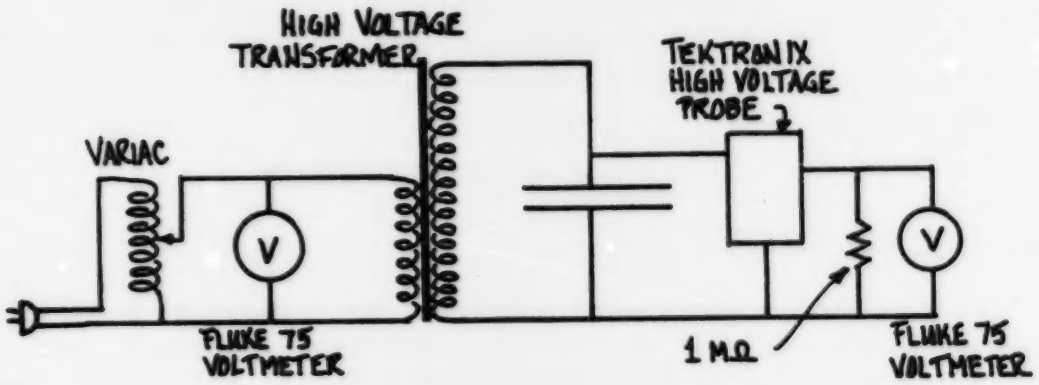

Figure 9. High voltage source. The Tektronix probe portion of this circuit was not used after the initial calibration.

The applied voltage was increased slowly, several kilovolts per minute, until a continuous or repetitive discharge occurred. Isolated discharges which occurred occasionally were ignored. The voltage that we recorded for the Tektronix high voltage probe was the voltage reading just prior to breakdown, since this voltage shifted upon the initiation of the discharge. There was no provision made for limiting the discharge current in our experiment although this would be advisable as a safety precaution and to limit possible damage to window coatings.

ELECTRICAL DISCHARGE RESULTS

Internal Electrodes

Initially a cylindrical plastic chamber was constructed with isolated electrical feed throughs made of number 12 gauge bare wire. This wire was rounded at the end so that its curvature was close to the wire's radius of 0.85 mm. The two wire electrodes were oriented at 90 degrees to each other's length with a gap spacing of approximately 0.57 cm.

The chamber was flushed with a selected air-argon mixture for 10 to 15 minutes at a total flow rate of 130 to 200 ml/s and then was sealed off using the inlet valve and a small rubber stopper in the 0.9 cm diameter exhaust port which was located on the top of the chamber. Care was taken to ensure that the chamber was not above atmospheric pressure and that ambient air did not enter by the exhaust port. At all times the flow of gas was sufficient to flush the 532 ml volume of the chamber at least 150 times.

Five minutes after filling the voltage was raised slowly until a continuous arc discharge occurred. The voltage was reduced quickly to around 70 percent of the breakdown voltage and slowly increased again. This was repeated until nine to twenty readings had been obtained for each gas mixture.

The average breakdown voltage is plotted in Figure 10 as a function of argon fill. Each set of nine readings had a standard deviation of 3-5 percent. The statistical error on the average voltage is thus in the range of 1-2 percent (standard deviation of the mean). The scatter about the trend curve of Figure 10 is predominantly due to a lack of precision in setting the gas mixture in this preliminary experiment.

The slope of the graph is such that for a gas fill of over 80 percent argon, a 2 percent accuracy in measuring the voltage corresponds to about a 1 percent accuracy in determining the proportion of argon in the gas mixture.

The breakdown voltage of 11.3 kV for pure medical air was reduced to 10.9 kV for ambient room air at 31 percent relative humidity. The effect of humidity on the breakdown voltage for air-argon mixtures could be studied as an extension to this work. Since most of the ambient air, with its moisture, is displaced by dry argon in fabricating the unit, moisture should not be a problem in the assembly plant measurement. On the other hand, measurements on IG units at the installation site and in long term field trials, could be affected by the penetration of moisture into the sealed unit.

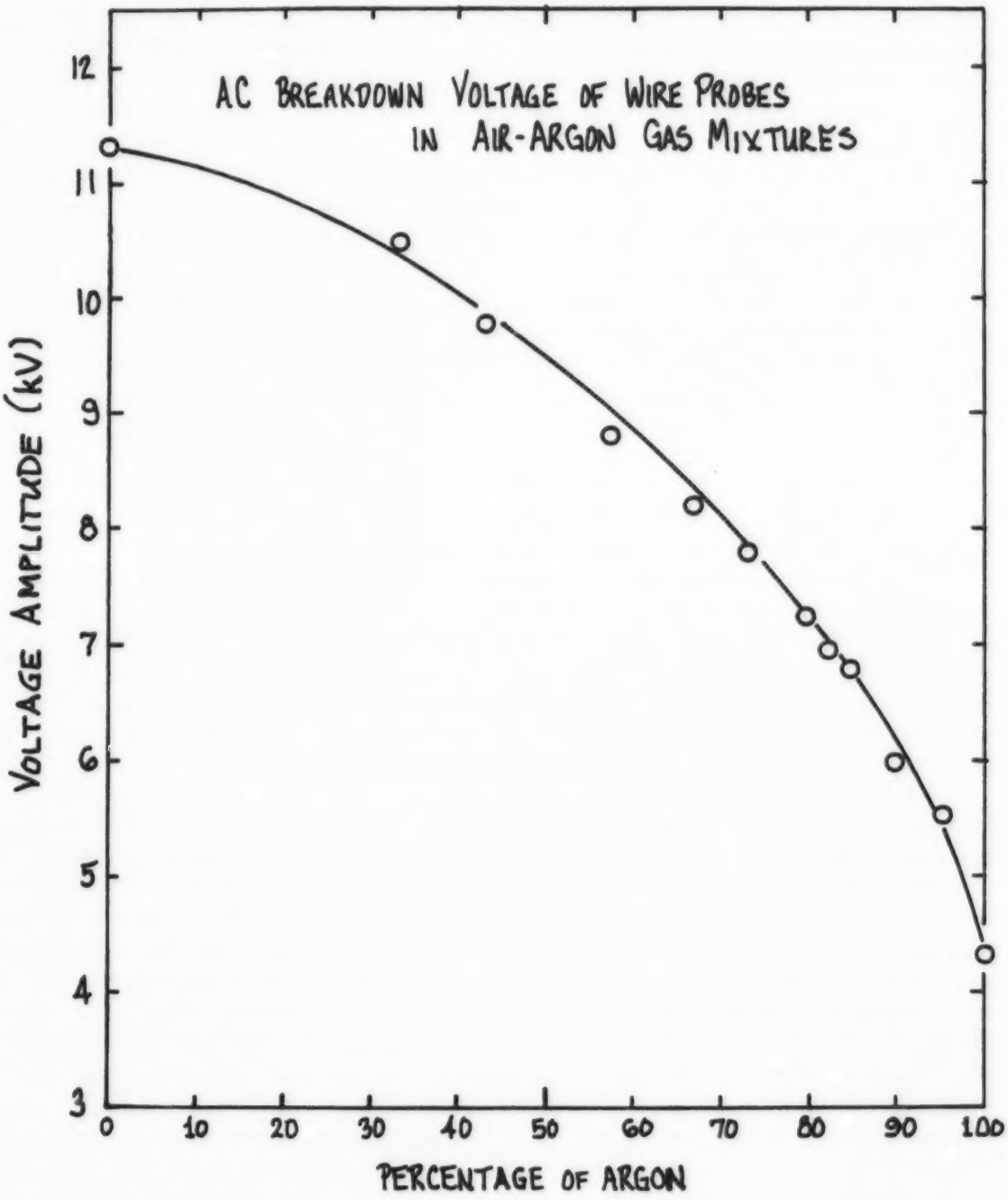

Figure 10. AC breakdown voltage for internal number 12 gauge bare wire probes as a function of the argon fill level in a plastic test chamber.

External Electrodes

An air-filled double-glazed window was obtained from PPG of Halifax with a sungate low-e coating on one of the two 3 mm plates. The window measured 0.25 m square with an air gap of 17.5 mm for a volume of 1094 l. Two 0.64 cm diameter holes were drilled in the spacer bar. A copper gas-flow tube was inserted into one of these and then sealed with Devcon sunroof and windshield sealer. The second hole was closed using the same sealant on a coated wooden dowel after each filling.

With a section of flexible tubing in the gas flow line we were able to fill the window in a vertical orientation with inlet and exhaust ports both on the top side. Again a 10 to 15 minute flush of the window ensured over 75 gas changes. After plugging the exhaust port the window was set horizontally with the low-e side on an aluminum plate. Our plate electrode was approximately the size of the unit, but it need only be 2 - 5 cm larger than the second electrode in order to provide an electrical infinite plane.

We had initially used a point electrode on the upper surface with the conducting plane on the lower surface, but this was not very reliable. With a point electrode geometry, there is a much smaller volume in which the electric field reaches the breakdown value. This increases the probability of reaching a large over voltage before discharge. The reduction in breakdown field with increasing electrode area has been described in detail by Endo *et al.*[8].

We replaced the point electrode with a 6.0 cm diameter conducting disc placed against the upper glazing. This parallel-plate geometry provided a large constant-field region. Since the region between the electrodes was now filled with a shower of discharges, the onset of breakdown was clearly identified either by visual inspection or by the associated sound. Consequently, the breakdown voltage was very repeatable. Typically we had a standard deviation of 1.0 percent and a standard deviation of the mean of 0.33 percent with 9 readings. In other words, if one only makes a single reading, the uncertainty is approximately 1 % on the voltage, but this can be reduced by repeated readings. This translates into a gas-fill level uncertainty which improves with argon content as shown in Table 2.

In our first set of measurements using the parallel plate electrodes, we only measured the voltage with the Tektronix probe. However, above the probe's rated value of 20 kV the AC signal was visibly distorted, as viewed on an oscilloscope. Hence we inserted the meter on the primary side of the transformer (see Figure 9) and repeated the measurements. The Tektronix probe was used at voltages below 15 kV to obtain a calibration factor for the step up transformer.

Table 2 : Potential precision of argon gas measurement by electric discharge method as determined from Figure 11.

Percent Argon Content	Accuracy on Percent Argon Content	
	Single Voltage Reading	Nine Voltage Readings
85.00	0.39	0.13
90.00	0.29	0.10
95.00	0.18	0.06

We have included both sets of measurements in Figure 11. It is important to realize that the final set of data, designated by the open circles and the trend line, was taken for a completely different sequence of gas fills.

Since we only have a 1 percent accuracy in determining the air-argon flow mixture, this is the limiting factor in the plotted data. The difference between the two sets of data at the low voltage end of the curve can be entirely attributed to a 1 percent discrepancy in the argon flow rate which remained fixed for all mixtures in a particular set of measurements. At voltages above 20 kV the distortion of the signal output from the Tektronix probe leads to a progressively underestimated peak value as can be seen in Figure 11.

A final potential problem must be considered. After the first few electrical discharges, we inspected the low-e coating for damage, but did not notice any. However, at the end of our experiments, after more than 600 major discharges, the low-e coating showed clear signs of damage. There was a speckle discoloration which at first appeared to be dust on the window and three major damage regions of less than 1 mm diameter. A few measurements, especially with a current limited by electronically switching the voltage off upon or just before breakdown, should not leave a visible problem. However, we do not know whether there will be a slow degradation of the low-e coating over time, nor do we know whether other types of coatings will show any damage. Until these questions are answered there are potential risks involved in commissioning an instrument for commercial use. For example, a glass supplier might not honor the warranty on his product if it had been subjected to this or other unproven test procedures.

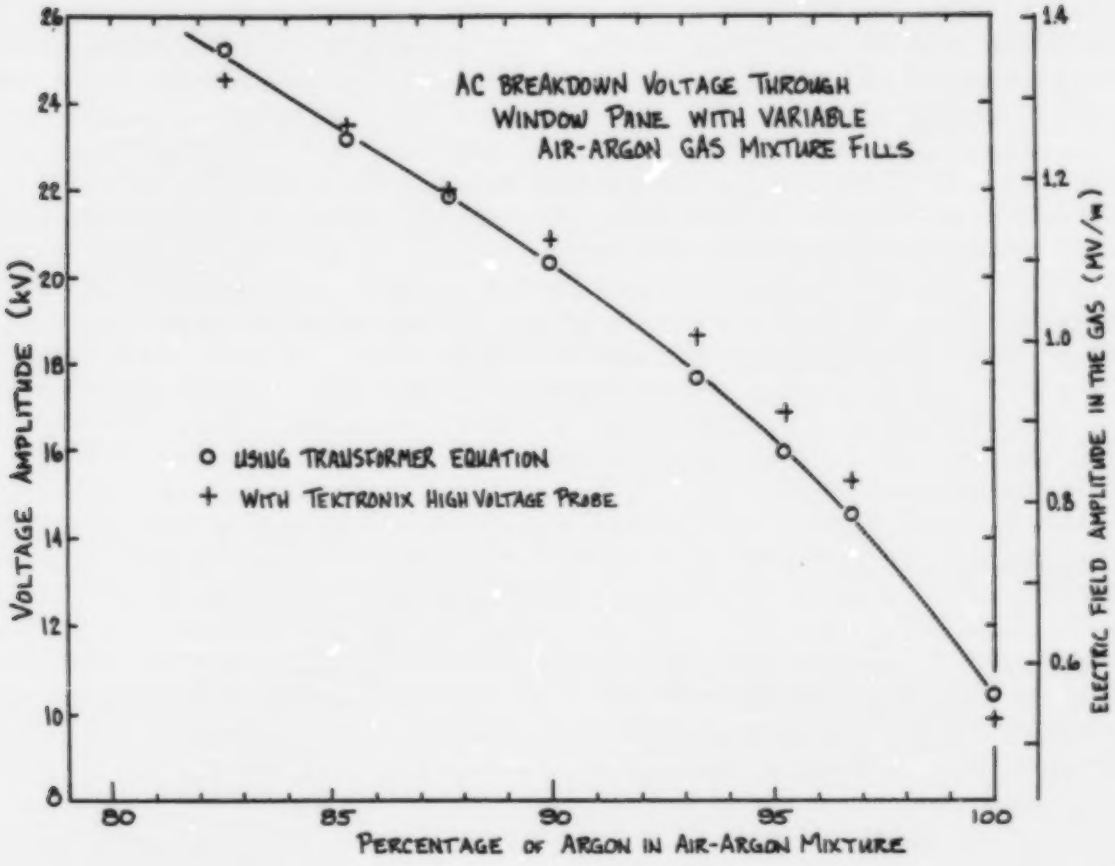

Figure 11. Electrical breakdown characteristics as a function of air-argon content in a window. The left hand axis is the measured peak voltage while the right hand axis is a calculated field strength.

Anomalous First Reading

The low Tektronix probe value at 100 percent argon fill is not consistent with the rest of the data and could not be repeated during the initial set of tests. We initially thought that this measurement might have been influenced by a fleck of metal from the drilling of the spacer bar, that was temporarily stuck to the inner glass surface. However, since this was the first point measured, it might be uniquely different for some other reason.

We tested several hypothesis for this anomalous first reading. Electrodes can have low initial breakdown voltages due to surface

roughness, since electrical breakdown will first occur at a point protrusion on a surface. After conditioning, during which these protrusions are burnt off, the breakdown voltage stabilizes. If this was the cause, then the lower initial breakdown value would not be repeatable. Therefore, in order to repeat the initial conditions, we flushed the window with medical grade air for 15 minutes, then refilled with 100 % argon and repeated the measurement at various time intervals. A low breakdown field was again measured immediately after the argon filling. Consequently, surface roughness was not the problem. However, one can not rule out gas born dust which can enter at each filling.

The breakdown voltage was then monitored over several days and was found to increase. The coated wooden plug was replaced with a copper pipe and valve so as to eliminate outgassing of fresh sealant from the exhaust-port plug. After several days the unit was again flushed with medical air and then filled with 100 % argon. The breakdown field rose 10 % in the first hour after argon filling and was up by 40 % after 24 hours. This corresponds to the variation expected for admixtures of 0.07 % and 3.2 % of air respectively (See Figure 11). We refilled the unit with argon without introducing air and found only a 12 % increase in breakdown voltage over 24 hours. Together these tests suggest that there is some initial outgassing from the walls.

Outgassing can have two possible influences on the breakdown voltage. Firstly, the admixture of the outgas can change the electrical properties of the filling-gas mixture as mentioned above. Secondly, the change in the surface composition might affect the electron emission probability from the electrodes (glass panes or their coating).

If it is the electrical properties of the gas mixture that are changed by the outgassing, then our calibration curve in Figure 11 is valid for the quoted argon-air mixtures. In other words, since the change due to outgassing is small over the 15 minutes taken for our measurements, the influence of outgassing will be minimal. In addition, our measurements were taken over several days during which time the unit was not exposed to more than 20 % air.

On the other hand, if a change in surface composition leads to the observed time variation, then a new calibration curve will be required at the steady-state value. Most likely this would result in a curve which is shifted up in voltage by less than 15 % from our results in Figure 11.

We are unable to determine the origin of this effect. Furthermore, the literature provides little guidance. We have only found one reference to electrode changes in an argon gas. Golden and Fisher[9] report approximately a 280 % increase in breakdown potential over 24 hours for metal electrodes in half an atmosphere of argon when a microampere of continuous discharge is present. In addition, they note that the change is more rapid with larger currents. They attribute the change, which reaches

400 % after several days, to electrode conditioning, but do not specify what process is taking place. Conversely, they see no electrode conditioning effect with hydrogen gas.

Hydrogen gas will react with outgassing oxygen from the electrodes to form water vapor. Our measurements with internal metal electrodes in argon have been reported above to be altered by only 4 % when dry air is replaced by air at 31 % relative humidity. Hence oxygen outgassing might not affect the hydrogen breakdown potential significantly.

On the other hand, oxygen outgassing will strongly affect the argon breakdown potential. However, the 400 % change that Golden and Fisher observe is far larger than the 150 % increase that we observe in Fig. 11 with a 15 % admixture of air. Therefore, it is impossible to attribute there large variation solely to oxygen outgassing. Further experiments are needed in order to identify the conditioning involved in their experiments and the time dependence in our measurements.

Furthermore, Beyer and Rtitschel[10] have studied the effect of humidity on the breakdown voltage of SF6. They observe little effect until the relative humidity exceeds 40 % when a decrease of 30 % in the breakdown voltage begins. Although the effect of humidity has not been systematically studied for argon, it is unlikely that humidity is the source of our observed time variation since we employed dry air in all mixtures. Nevertheless further tests should also consider this possibility.

Clearly, there is a need for further controlled experiments to resolve these questions before the ultimate precision of the electrical discharge technique can be realized.

Adaptation to Other Glazings

Our window measurements were all made on a single double glazed unit. However, these results can be applied to other glazings. As illustrated in Figure 12, the applied voltage V is the sum of the voltages across all layers of the system.

$$V = V_1 + V_2 + V_3 \qquad (5)$$

Furthermore, for the constant field geometry used here, one has for the i^{th} layer

$$V_i = E_o d_i / \varepsilon_i \qquad (6)$$

where E_o is the field strength in the air-argon mixture where the dielectric constant, ε, is approximately one. Consequently,

$$V = E_o \sum d_i / \varepsilon_i \qquad (7)$$

is the required breakdown voltage if E_0 is the breakdown field for the gas. This can be applied to double, triple, etc. glazings by summing over all the additional terms.

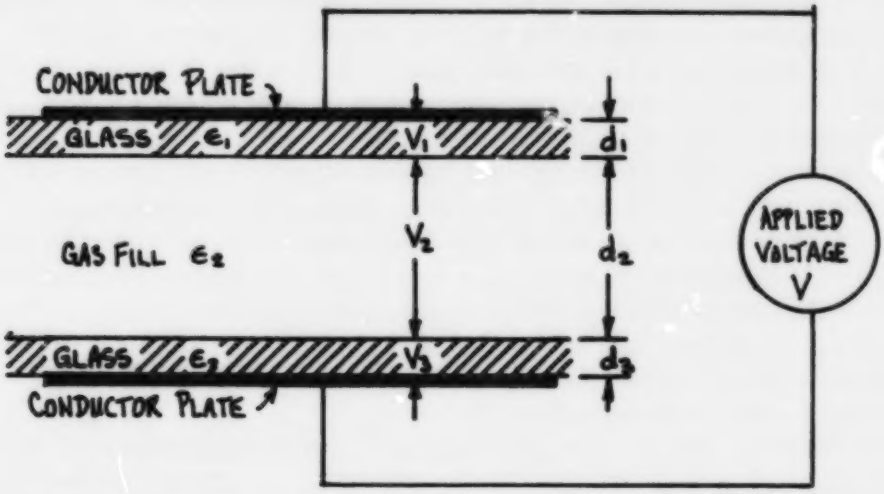

Figure 12. Relation between applied voltage and gas breakdown voltage in the window gap.

The theory is not modified if there is a low-e coating, or any other conductive coating, on any of the surfaces, unless the coating is on a flexible surface that is not parallel to the other glazings. Since the low-e coating is a conducting layer it defines an equipotential surface and hence must be parallel to the electrode planes. Otherwise the field strength will not be uniform.

We used Eq.(7) to obtain the dielectric constant for our glass. In order to fix the air-argon mixture we sealed the test window. The breakdown voltage was measured for the window alone. Then three measurements were made with two additional glass plates. With one additional glass plate set against each glazing of the window a new breakdown voltage was obtained. The procedure was repeated with both of the additional glass plates on one surface. Then a third set of measurements was made in the original geometry of one plate on each side of the window.

These additional PPG plates had a thickness of 2.4 mm. The ratios of the breakdown voltage with the additional plates to that of the window alone from our three tests were 1.050 ± 0.008, 1.049 ± 0.011, and 1.052 ± 0.004. Using an average value of 1.050 we solved for the unknown dielectric constant obtaining a value of ε = 5.17. This is in good agreement with Pulker's[10] value of 5.1 for soda lime borosilicate glass. Since glass properties can be quite variable this close an agreement is probably fortuitous. Nevertheless, we have used this value of ε = 5.17 in Eq. (7) to

convert the measured breakdown voltages for our window into the breakdown field in the gas cavity. This scale also appears in Figure 11 and can be used with Eq. (7) to apply these results to other window geometries.

As a cross check, further tests were carried out on two independent window units that had been provided by Cardinal IG. Both units had a gap spacing of 1.13 cm and 2.4 mm glazings, but only one unit had a low-e coating. The clear glass unit had been filled at Cardinal's plant with 1.00 % O_2 , 1.00 % N_2 and 98.00 % argon using a calibrated gas standard. Using Eq.(7) to account for the different dimensions, this window should require breakdown voltages that are 65.8 % of the values given in Figure 4. Electrical discharge measurements for this new window yielded a value of 97.3 ± 0.2 % for the argon content. This is within the 1 % precision of our estimate of the electrode spacing. However, there were three differences between this unit and our first test unit. This unit did not have a low-e coating, the contaminant gas did not have the same proportions as air and the electrode spacing was reduced.

The two new units from Cardinal IG enabled us to investigate each variable separately. We drilled filling holes in both of the new units and flushed with 100 % argon gas. The breakdown potentials of the new IG units were 6.66 ± 0.07 and 6.71 ± 0.05 kV for the low-e and clear glass units respectively. The agreement between these readings confirms that the presence or absence of a low-e coating has little or no effect on the sparking potential. In other words, it appears that the zinc oxide, which is applied as a protective overcoating for the low-e silver film, has electrical properties that are similar to those of glass.

The dependence on electrode spacing, as described by Eq.(7), was checked by calculating the breakdown field at 100 % argon for all units. The breakdown voltages for the 1.13 cm spacing convert to E_0 = 0.545 ±0.008 and 0.549 ± 0.007 MV/m for the low-e coated and clear glass respectively. A 1 % uncertainty on the electrode spacing is included. These values agree with the estimate of E_0 = 0.558 ± 0.007 MV/m that was obtained with the original unit at 1.75 cm spacing.

As a final test, the clear glass unit was filled with a 90.6 ± 1.0 % argon mixture. Using Eq. (7) and Fig. 11 we obtained a measured argon content of 91.0 ± 0.2 %. Consequently, the dependence on air-argon gas mixture also does not depend strongly on the glass coating. However, to confirm each of the above assertions more extensive systematic tests are required with a more precise knowledge of the gas mixture.

In one of the measurements on the Cardinal IG units, we recorded an AC current of 120 μA in the high voltage circuit during discharge. Therefore, the power requirements for the discharge method are on the order of Watts.

DISCUSSION

Table 3 summarizes our main results with some general comments on the different approaches. We will discuss only the two most promising techniques - the electrical discharge and the time-of-flight measurements.

Of the techniques that we used, only the electrical discharge technique has sufficient precision to be useful with an argon gas fill. Furthermore, we expect that the discharge technique will be equally applicable to the heavier inert gases, such as krypton and xenon, since they have similar ionization energies. This view is supported by the results of Pejovic *et al.*[12] who have measured static breakdown voltages of 382, 400 and 500 V for argon, krypton and xenon respectively at low pressures of 13.3 mbar in diode experiments.

On the other hand, because SF6 is an insulator, the breakdown voltages are greater than those for air. For pure SF6 Bhalla and Craggs[13] report a breakdown field of 89.3 kV/cm at atmospheric pressure as compared to the value of Jones and Parker[14] of 28.7 kV/cm for pure air. Consequently SF6 gas mixtures would require higher voltage requirements and a greater potential electrical hazard.

There is no published data available for the electrical breakdown characteristics of SF6 plus argon mixed with air. In general, published work on SF6 mixed with other gases addresses the problem of finding a less expensive mixture that remains a good electrical insulator. Consequently existing publications are not directly applicable to the present study of gas-filled windows. However, some trends in the existing SF6 measurements are useful when discussing our argon results (Representative experimental data on SF6 mixtures is summarized in References 15 and 16 as well as the theoretical papers of Brand and Kopainsky[17], Raju and Hackam[18] of University of Windsor, and Frechette and Novak[19] of IREQ at Varennes Quebec).

As is illustrated in Figures 10 and 11 of this report, the breakdown voltage changes most rapidly near a 100 % argon fill. In other words the greatest sensitivity occurs when small amounts of the more insulating gas, air in our case, is added. In Figure 9 of Brand and Kopainsky[17], additions of up to 10 % of the more insulating SF6 to nitrogen gas results in large changes in the breakdown field. This trend of a large variation in the breakdown voltage with a small addition of a more insulating gas is consistent with our argon measurements, as is the decrease in the rate of change of breakdown voltage with gas mixture as the more insulating gas becomes the more abundant component.

Table 3 : Evaluation of the measurement techniques that were considered in this report.

Parameter	Electrical Discharge	Acoustic Time-of-flight	Acoustic Resonance	Thermal
Argon content precision	1 reading 0.3% 9 readings 0.1%	20%	20%	poor
Heavy-gas content precision	inert gas-as above; insulators(SF6)-unknown	2%	5%	probably few %
Time for pass/fail test	1 sec.	1 sec.	1 min.	30 min.
Time for % content	1-10 min.	< 1 min.	1 min.	30 min.
Ease of use	easy	less easy	difficult	easy
Technical expertise	low	highest	medium	medium
Special requirements	electrical hazard precautions	100 kHz noise isolation	low noise room	thermally stable room
Test position	10 cm clear of spacers	10 cm clear of spacers	position sensitive	clear of spacers
Double glazing	Yes	Yes	Yes	Yes
Triple glazing	internal probes-Yes; external probes - highest level	transmission signal problems	transmission signal problems	Yes
Equipment costs in $1000.	2 - 5	15 - 30	-	-

We speculate that some mixtures of SF6 and argon will have little variation of the breakdown voltage with admixtures of air due to their offsetting electrical properties. Consequently, it is not clear that the electrical discharge technique will be useful with SF6 mixtures or other electrically insulating gases.

For SF6 and other gas mixtures where the electrical discharge technique is inadequate, the time-of-flight measurement offers the next best solution for heavy gases. Indeed, in order to cover all possible gas-fill scenarios, one might need both measurements.

The time-of-flight technique does not give the resolution of either the Raman scattering or electric discharge measurements. Hence it is less suitable as a standards or research tool. However, either the time-of-flight or the electric discharge could replace the servomex type instrument as a quality control test since they have the advantages of being faster and nonintrusive. (The Raman scattering measurement is not suitable for production-line tests because of its low signal levels and noise sensitivity.) The obvious advantage to the time-of-flight approach is the avoidance of the high discharge voltages. The clear disadvantage is that it is not useful with argon.

Where the electrical discharge technique is applicable, its precision is equal to that of the Raman scattering measurements when the gap dimension and glazing characteristics are known. These parameters will be known or can be determined in a research environment where performance tests are the objective. In a production line where the objective is quality control an uncertainty as to the gap spacing and glass properties will only introduce a few percent uncertainty in the gas content which is tolerable. In the field where bowing of the sealed windows due to pressure, temperature, wind, etc. effects might occur, a precision of a few percent can still be achieved by taking readings near to the spacer bar rather than in the center of a large unit.

The electrical discharge measurement has some clear advantages over the Raman measurement. It is far less expensive ($2000 - 5000 vs $50,000 - 100,000), is faster, requires much lower technical expertise, is portable and can be used equally well in field work, on the production line or in standards testing. In fact, since the power requirements are on the order of Watts, an instrument can be built which can be used on the construction site even if permanent power is not available. On the other hand, some disadvantages of the electrical discharge technique are the potential electrical hazard and potential damage to window coatings from equipment failure or operator error.

The Raman technique achieves a higher precision than the servomex oxygen-detection instrument because it detects the more abundant nitrogen molecule. The electrical discharge voltage depends strongly on any dilution of the most abundant element argon. Therefore, equivalent precision can be achieved with much less sophisticated equipment.

With the electrical discharge method, there are two ways to eliminate uncertainties which are introduced by the glass properties and gap spacing:

(1) One can use internal electrodes, within the gas-fill region. These might be preferred in a test or research trial, but could meet with consumer resistance if introduced into the general production run. This geometry also eliminates possible variations in the electrical properties of the glass and its coatings.

(2) With external electrodes, one could analyze the light emitted from the discharge. Argon, oxygen and nitrogen all have characteristic strong spectral lines that could be used to determine the gas mixture. A twin detector system would be required because of the intermittent nature of the discharge in space and intensity. Like the Raman scattering experiment, this approach would be independent of unit construction parameters. However, unlike the Raman technique the light which is emitted from the discharge could be detected using relatively inexpensive filters and optics so that the cost would remain low.

The KONAR instrument which is still at a prototype stage is also based on the electrical discharge properties of the gas fill. However, since the high voltage is produced using a coil and spark gap the voltage amplitude is not highly repeatable. This variability in the amplitude of the voltage makes accurate measurements impossible. Although it cannot be used as a standards-grade instrument, it does provide a useful pass/fail test instrument.

Basically, KONAR is a tesla coil which can be purchased from any scientific equipment supplier. Central Scientific[20] lists two models, the basic one at $115 and a more expensive one at $290. One uses an IG unit filled to the pass level as a reference to adjust the spark gap until electrical discharge just occurs. If the tesla coil is held against a test sample whose fill level exceeds the pass level, then visible sparking occurs.

Our electrical discharge uses a transformer to produce a repeatable 60 cycle high voltage so that it is inherently more stable and hence capable of precise measurements. It can also be used in the pass/fail test mode by leaving the voltage at a preselected value. Alternately, an analog meter with pass/fail coded zones on the scale can be used with an automated instrument. The presence or absence of a low-e coating in principle has no effect on the measurement, but separate calibration curves might be required for coated and uncoated glazings.

Contrary to the statement in Ref. 2, KONAR also does not require a low-e coating to function, as long as one provides a grounded conducting plate on the opposite side of the IG unit. This also will be the case with any commercial tesla coil.

CONCLUSIONS

Our objective was to determine the feasibility of measuring the gas content of an IG unit with a nonintrusive technique. This objective has been reached. The electric discharge measurement is capable of standards quality measurements. However, to achieve this capability further systematic tests are required.

Tests which should be made before a commercial product is designed and built include the following. The tolerance of the low-e coating to different degrees of electric discharge must be determined over both the short and long term. Also, more precise calibration curves for argon-air mixtures are needed, as are calibration curves for other common gas mixtures. The dependence of the breakdown field on the time from filling must be determined. The dependence on pressure and moisture content must be tested. Finally, as is apparent from Figure 7 of Golden and Fisher[9], at pressures of one atmosphere the breakdown electric field strength has a slight dependence on the gap spacing. Consequently, a set of calibration curves at the standard window-gap spacings should be generated.

Without further tests the electric discharge method will have an uncertainty of a few percent in the argon content which is sufficient for production line applications. At the same time, it is inexpensive as a quality control device.

Moreover, the precision of this method might be further enhanced by coupling it with an optical analysis of the light emitted from the discharge.

As mentioned in the introduction, when performing accelerated weathering tests one measures the gas content and the leak rate. James Larsen of Cardinal IG[3] is considering using Raman measurements separated by four weeks to obtain the leak rate. This would eliminate the need for Linde test equipment. Since our electric discharge technique is capable of the same precision as the Raman technique it also could make both measurements. The time between measurements might be reduced if the proposed optical analysis improves our precision.

RECOMMENDATIONS

The long term effects of the electric discharge on the low-e coating must be tested. In particular, the effect of adding air and/or moisture at some time after the discharge should be determined.

The electrical discharge voltage should be measured for different gas mixtures. We recommend that these measurements be made with a special test chamber which includes a mass quadrupole

for precise measurement of all gas components including moisture content. The gas analysis capability is important, since one must know the actual gas composition as it might change from the initial filled state. The chamber should also include pressure instrumentation.

The optical analysis of the electrical discharge should be pursued as it might have greater precision. Furthermore, it is a direct measurement which contains more information as to the type of gas in the unit. Consequently, it has the advantage that one does not need to know the past history of the IG unit.

Our electrical discharge measurements were all made with 60 Hz AC voltages. The sensitivity of the technique should be tested at other frequencies.

The time-of-flight technique warrants further study. Since we did not have a digital storage oscilloscope we could not fully test the capabilities of this method.

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